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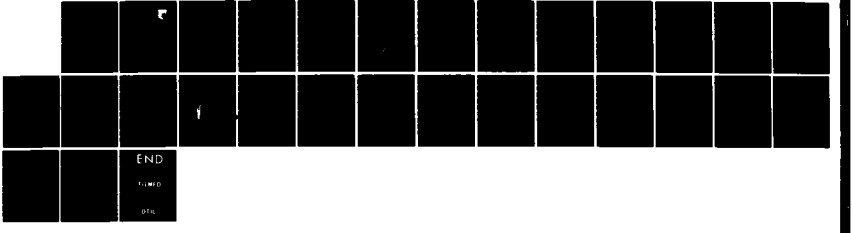

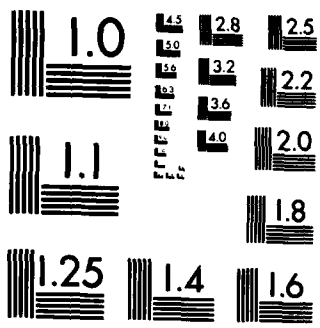

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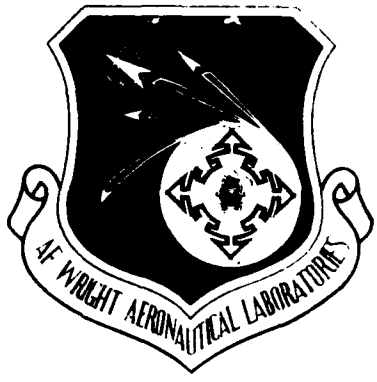

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A STANDARD AIRCRAFT DIFFUSION FLAME: SPECTRAL CHARACTERISTICS AND A FEASIBILITY STUDY FOR DEVELOPING AN ALTERNATE CALIBRATION SOURCE FOR AIRCRAFT OPTICAL FIRE DETECTION SYSTEMS

R.L. Hawkins and K.N. Rao

THE OHIO STATE UNIVERSITY
DEPARTMENT OF PHYSICS
174 WEST 18TH AVENUE
COLUMBUS, OHIO 43210

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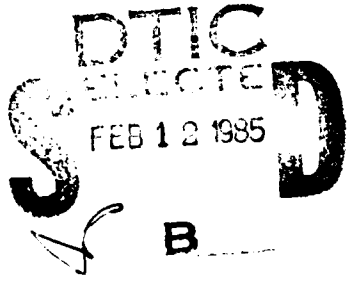

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The standard aircraft diffusion flame source presents practical difficulties due to its lack of controllability and its production of large amounts of smoke and soot. A source which is more convenient to handle, but which emulates the spectral and power characteristics of the standard flame, might prove useful. The requirements of such a flame were evaluated by measuring the spectral and power characteristics of a standard aircraft diffusion flame over the spectral range 2.5 μm to 20 μm. The total power output in this range was on the order of 1000 watts. About one-fourth of this was from the 4.4 μm carbon dioxide emission band; a small amount was due to weaker emissions of water vapor and carbon dioxide; and the remainder was due to thermal emission from soot particles.

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INTRODUCTION

A common method of detecting fires is the direct sensing of optical radiation emitted by the burning material. When the burning material produces radiation with a distinctive wavelength dependence, it is possible to discriminate between radiation from a fire and other background sources.

Linford and Dillow (1)* measured the radiation emitted by a variety of hydrocarbon aircraft fuels and lubricants, from the middle ultraviolet to the far infrared. They suggested considering the use of the CO_2 emission at 4.4 μm in the infrared for fire detection. This emission band was the dominant one for all of the aircraft combustible fluids studied, and there were no strong emission features at nearby shorter wavelengths. This would permit easy discrimination between emission due to burning fluids and broad-band sources, such as heated solid surfaces.

The work described in this report was undertaken to measure the infrared emission from a burning pool of JP-4 aircraft fuel (as opposed to the pressurized jet of JP-4 fuel used by Linford and Dillow). The spectral distribution from 2.5 to 20 μm was measured using Fourier Transform Spectroscopy, and the integrated intensity of the 4.4-μm radiation was determined relative to a calibrated blackbody standard. These measurements were combined with a direct measurement to determine the total power output in the 2.5 to 20 μm range.

With this information, it is possible to specify the total power and spectral distribution required of an alternate calibration source.

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*(1) R. M. F. Linford, C. F. Dillow and T. M. Trumble, J. Aircraft 14, 481 (1977).

EXPERIMENTAL DETAILS

SOURCE:

The burner used in these measurements was a cylindrical metal can, 5 cm (∿ 2 inches) in depth and 12.7 cm (5 inches) in diameter. It was filled with JP-4 turbine fuel to an initial depth of 2.5 cm (∿ 1 inch). This conforms with MIL-D-27729A (USAF), paragraph 4.5 (2)*.

The burner was contained in an aluminum box which was open at the bottom and connected to an exhaust fan at the top, so that air-flow was upward past the burner. The box was 91.5 cm tall by 25.4 cm by 25.4 cm, and the exhaust pipe was 10.2 cm in diameter. The exhaust rate was barely sufficient to prevent smoke from escaping into the optical path. A 7.5-cm-diameter hole in one side of the box allowed the viewing of the radiation. The height of the burner inside the hood was adjustable. A diagram of the burner and hood is given in Fig. 1. All spectral measurements were taken under ambient atmospheric conditions.

---

*(2) "Test Fire and Response Rates - The flame and the smoke sensors shall be calibrated and adjusted to respond to a rapidly burning 5-inch diameter pan of gasoline (100 octane) or JP4 fuel with and without the addition of 30 percent by volume of hydraulic fluid. The flame sensor shall respond within 150 milliseconds when exposed to the fire which has been burning for 30 seconds when the sensor is aimed directly at the flame base and at a distance of 4 feet from the flame."

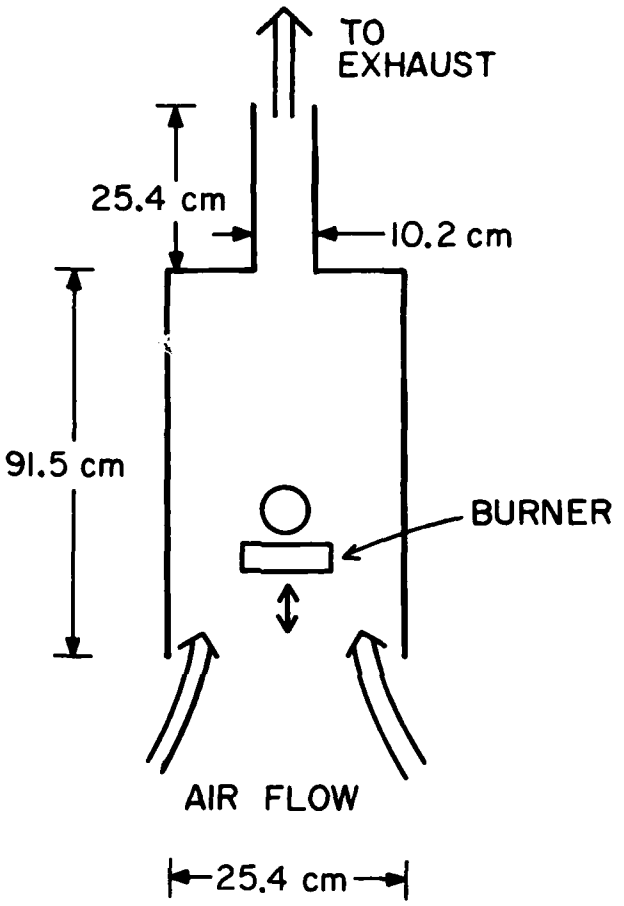


Figure 1. Burner and Hood

FOURIER TRANSFORM SPECTROMETER (FTS):

Emission from 2.5 μm to 20 μm (4,000 cm^{-1} to 500 cm^{-1}) was measured using a Nicolet 7199 Fourier Transform Spectrometer and Nicolet 1180 computer, with a mercury-cadmium-telluride (MCT) detector. A diagram of the FTS system is given in Fig. 2. The response of the FTS system peaks at 12 to 20 μm and decreases steadily to 2.5 μm. The actual response characteristics are given later in this report. It was anticipated that the flame spectrum would be dominated by a relatively narrow peak due to the 4.4 μm emission of CO_2. Such narrow-featured spectra are subject to phase errors when measured with FTS instruments. Therefore, a spectrum of a Globar source (an electrically heated ceramic rod) was taken immediately before taking the flame spectrum. The broad-band, slowly varying Globar spectrum provided a phase calibration for the flame spectrum.

The resolution of the Fourier transform spectrum was 2 cm^{-1}.

PRISM MONOCHROMATOR:

The intensity at 4.4 μm was measured using a prism monochromator and a calibrated blackbody source. This system is diagrammed in Fig. 3.

The prism monochromator was a Perkin-Elmer Model 160 foreprism modified with an external exit slit. The double-passed prism was potassium bromide (KBr).

To provide a calibration for the flame radiance measurements, a blackbody reference standard with a 2.54-cm (1-inch) aperture was placed beside the flame hood. A rotating mirror was used to select either the flame or reference source. The source optics were designed so that the image of the

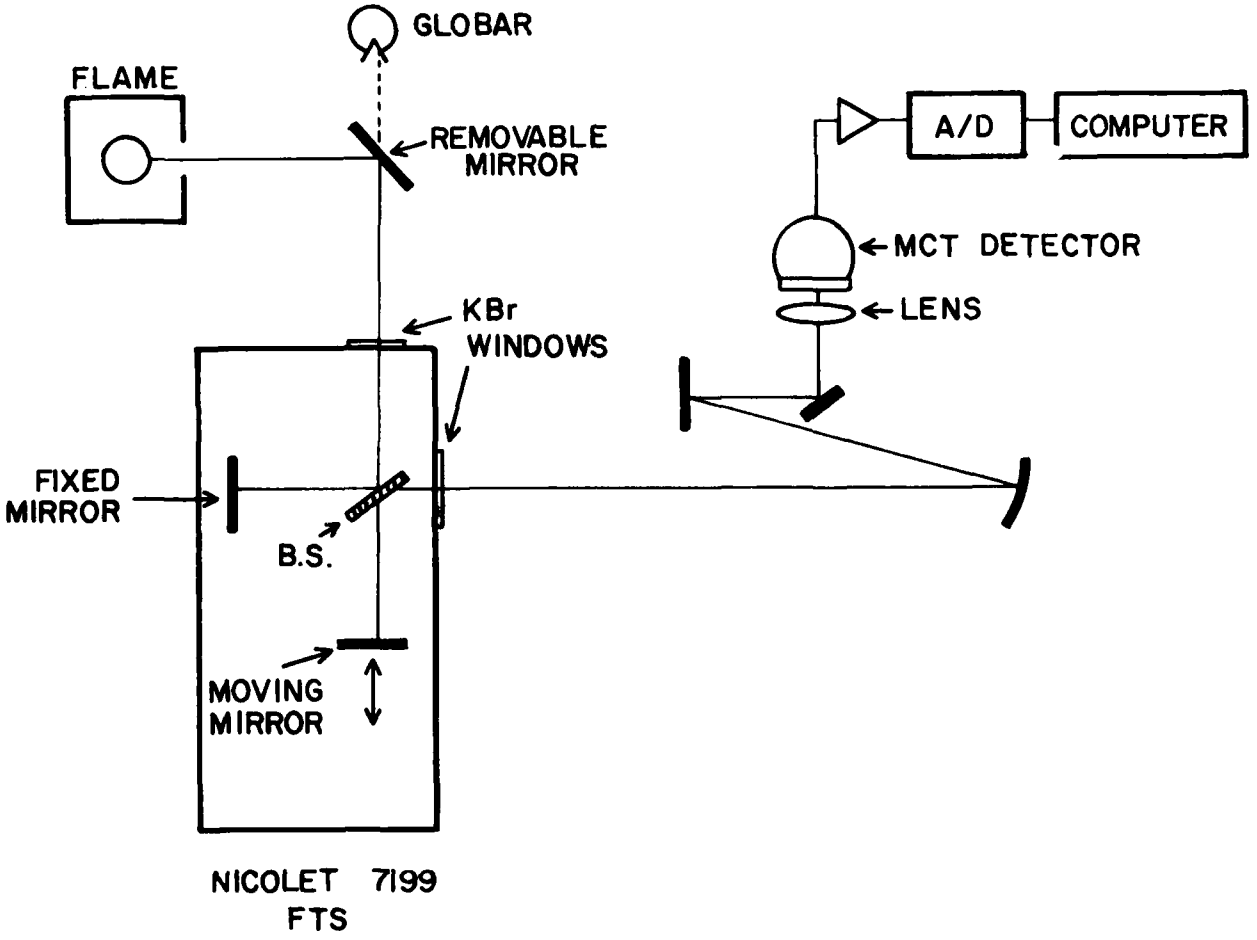


Figure 2. Nicolet Fourier Transform Spectrometer System

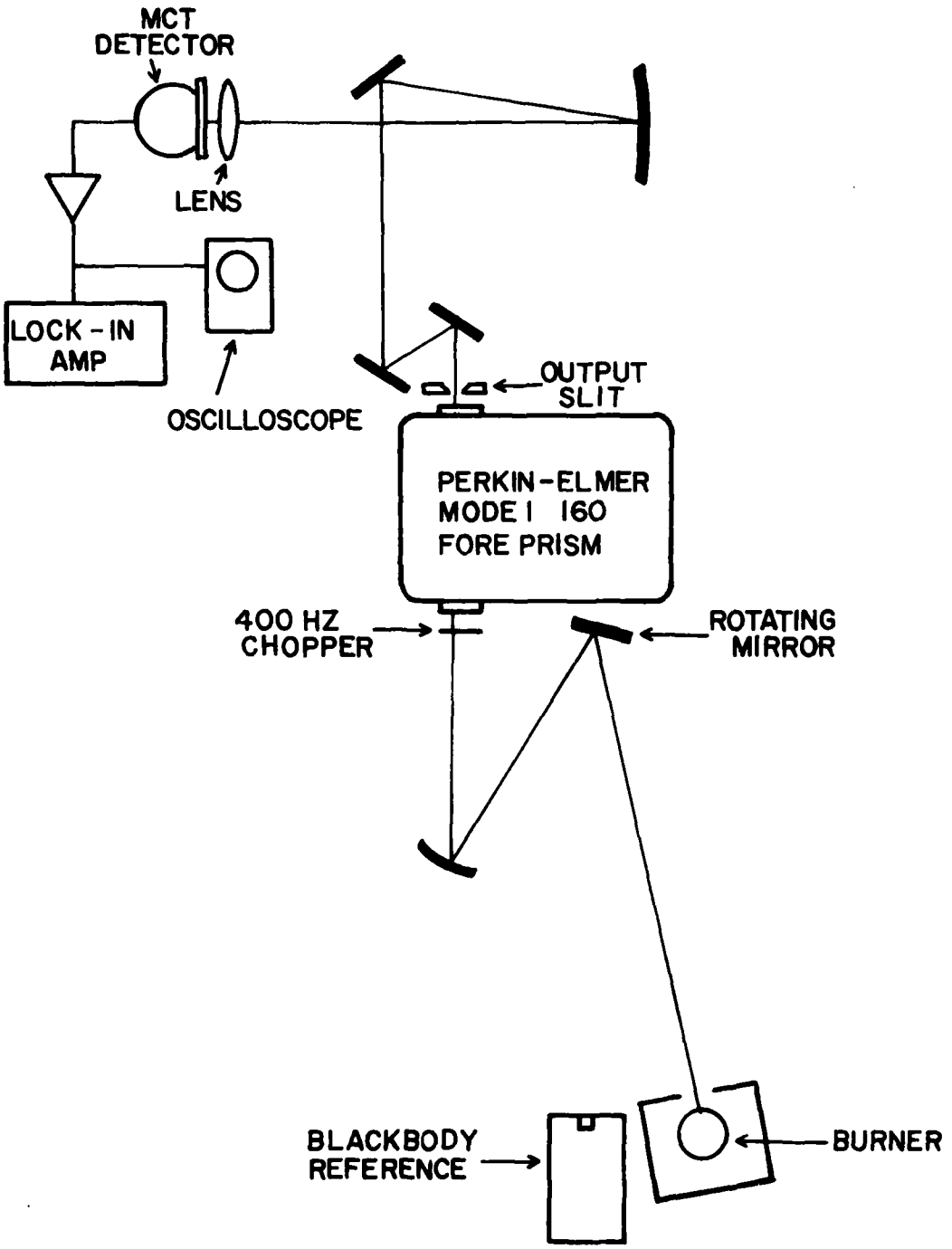


Figure 3. Experimental Set-up with a Prism Monochromator

blackbody aperture filled the foreprism's entrance slit. To further assure that the instrument's field-of-view was the same for the flame and blackbody, an aluminum foil mask was cut and placed over the entrance slit to vignette the upper and lower edges of the blackbody aperture. The resulting effective aperture height was 2.4 cm. At 4.4 μm the slit widths were 0.0525 cm, chosen to give a resolution comparable to the width of the 4.4-μm CO_2 emission. The signal was detected with a cryogenically cooled indium antimonide (InSb) detector, amplified by a PAR Model 124 lock-in amplifier, and recorded manually.

BLACKBODY REFERENCE:

The blackbody reference standard was an Electro-Optical Industries Model H5153, provided and calibrated by the Air Force Measurement Standards Laboratory/Aerospace Science and Metrology Center. Its emissivity was given as 0.998 ± 0.01. Its temperature was measured with a Type S thermocouple, with corrections as provided by AFMS/AGMC. The largest (2.54-cm) aperture was used throughout.

It was confirmed that moving the blackbody to the position normally occupied by the flame did not change the measured radiance within the precision of measurement (± 0.8%).

OPTICAL FILTERS:

Measurements were also made using narrow-bandpass optical filters as the wavelength-sensitive element. However, these measurements turned out not to be useful, as detailed in Appendix B.

TOTAL INFRARED OUTPUT:

To measure the total power output of the standard flame in the IR, an MCT detector was placed 121 cm (4 feet) from the burner with no intervening optics. A 390-Hz chopper was placed in front of the detector to modulate the radiation. The detector output was fed to a PAR Model 128 lock-in amplifier for measurement. The burner was in the hood described earlier, but a 15-cm wide by 30-cm high opening was used to allow the entire flame to be in the field-of-view. Alternately, a 0.16-cm (1/16-inch) aluminum plate, with a 2.54-cm-diameter hole cut in it, was used to mask-out all of the flame except a 2.54-cm-diameter circle 3.8 cm above the rim of the burner, simulating the field of view used in the prism measurement. This allowed the total-flame measurements to be related to the earlier blackbody-calibrated partial measurement.

EXPERIMENTAL RESULTS

FTS MEASUREMENT:

The Nicolet FTS was used to obtain a survey spectrum for qualitative comparison with emission spectra of other aircraft combustible fluids. This spectrum is plotted in Fig. 4. As anticipated, the spectrum from 2.5 μm to 20 μm is dominated by the 4.4-μm CO_2 emission. There is also H_2O at 6.5 μm and CO_2 emissions at 14 μm, somewhat exaggerated in Fig. 4 by the greater system response at longer wavelengths.

For comparison, Fig. 5 is an FTS spectrum of the blackbody calibration source, ratioed against the theoretical blackbody curve. The envelope of this spectrum is the relative spectral response of the FTS as a function of wavelength. The absorptions in this spectrum are due to atmospheric CO_2 and water vapor. CO_2 absorption occurs at 4.4 and 15 μm, water vapor at 6 and 17-25 μm (the apparent features at 10 and 13 μm are absorptions of the KBr-Germanium beamsplitter in the FTS).

PRISM MEASUREMENT -- 4.4 μm:

Measurement of the energy emitted at 4.4 μm was made for comparison with previous measurements, and for evaluation of the stability of the flame source.

The signal was observed at several heights to find the one which provided the maximum signal. Maximum signal was obtained wih the field-of-view

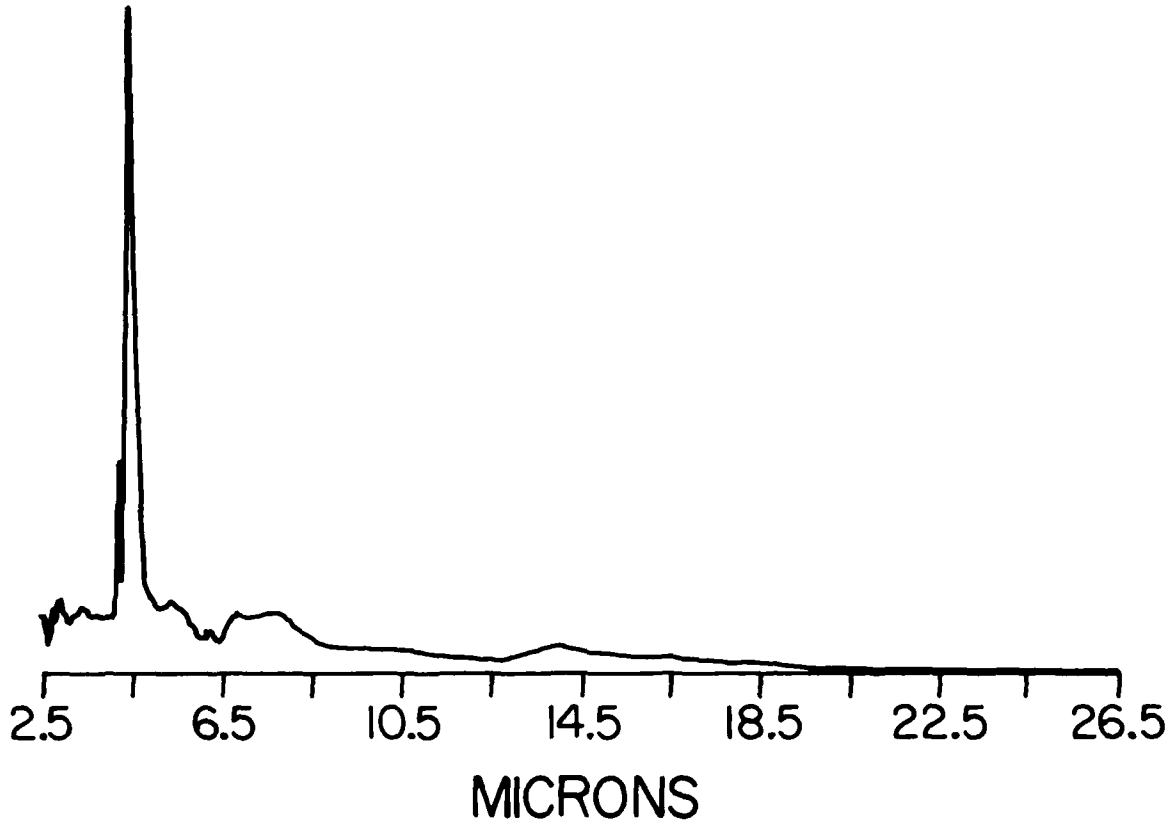


Figure 4. FTS Scan of the Aircraft Diffusion Flame
(Relative Intensities)

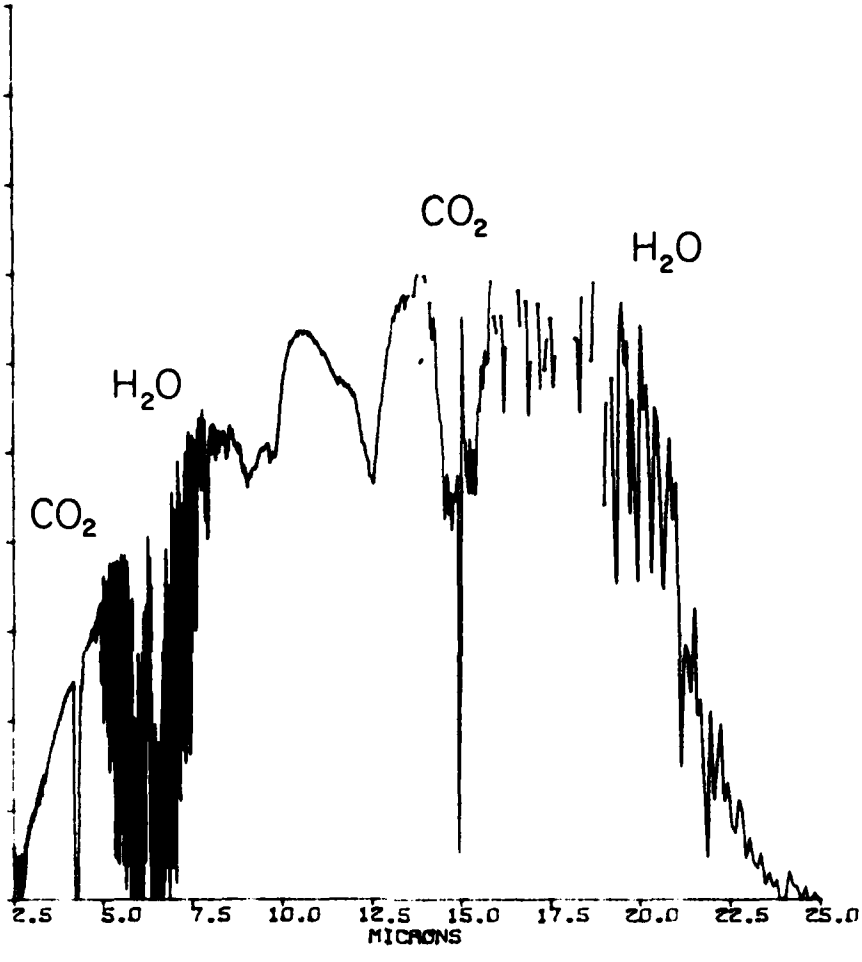


Figure 5. FTS Spectrum of the Blackbody Source, Ratioed Against the Theoretical Blackbody Curve (Relative Intensities)

centered about 3.8 cm above the rim of the burner. With the field-of-view centered 1.3 cm above the rim, the signal was reduced by one-fourth (from 16.5 mV to 12.1 mV ± 0.1). All subsequent measurements were taken with the field-of-view centered 3.8 cm above the rim of the burner.

The signal fluctuated by approximately a factor of 2 every 0.5 sec., by a factor of 3 every 10-12 sec. The fluctuations were rapid variations down from the peak level and appeared to be caused by flickering of the flame. A time constant (associated with the lock-in amplifier) of 10 sec. was therefore used for all flame measurements. The uncertainty in these measurements is a rough estimate of the RMS fluctuations remaining with this time constant.

There was no evidence, within the precision of measurement, that the radiance at 4.4 μm changed as the JP-4 fuel burned. Table I summarizes the results.

TOTAL IR OUTPUT MEASUREMENT:

The total output of the flame increased rapidly in the first few minutes after it was lit, perhaps due to heating of the fuel, leading to a faster vaporization and a higher rate of combustion. The flame grew in size noticeably over this period. The output leveled off after about 4 min.

When the detector was placed at 121 cm (4 ft), the maximum signal detectable with the lock-in amplifier (250 mV) was exceeded after about 2 min. Therefore, the flame was momentarily extinguished, and the detector moved to a distance of 230 cm (∿7 ft) before continuing. The results of these measurements are summarized in Table II. (The values in the table have been corrected for the background signal of about 7 mV present with no flame). As

Table I. 4.4 μm RADIANCE

Blackbody Reference:	
Temperature	1152 K
Signal	14.1 mV (± 0.1)
Flame:	
Signal	16.5 mV (± 0.1)
Radiance (Total)	8.1 W $\mu m^{-1} sr^{-1}$
Radiance (per cm^2)	1.73 W $\mu m^{-1} sr^{-1}$

Table II. DETECTED VOLTAGE OF ENTIRE FLAME (NO MASK) AND OF 12.54-CM-DIAMETER PORTION (MASKED)

At 4 ft.:	1 min.	2 min.
No mask	141.8 mV	242.0 mV
Mask	15.5 mV	17.0 mV
Ratio	9.1	14.2

At 7.5 ft:	1 min.	2 min.	3.5 min.	5 min.	6 min.	7 min.
No Mask	56.3 mV	71.6 mV	79.6 mV	101.6 mV	95.6 mV	95.6 mV
Mask	6.1 mV	6.6 mV	7.6 mV	9.4 mV	11.6 mV	11.5 mV
Ratio	9.2	10.8	10.5	10.8	8.2	8.3

might be expected, the signal fluctuations were quite large, and a time constant of 10 sec was used to get reasonably consistent readings.

Based on the signal measured at 121 cm, the inverse square law predicts that the first two measurements at 230 cm should be 40 mV (actually turned out to be 56.3 mV) and 69 mV (actually 71.6 mV) for the whole flame, and 4.4 mV (actually 6.1 mV) and 4.8 mV (actually 6.6 mV) for the masked flame. The actual values were somewhat higher, but since the fuel was not permitted to cool completely before being lit again, this would be expected.

A rough estimate of the total IR power output of the flame can be formed by the following chain of reasoning, ignoring any angular dependence of the flame radiation:

The measurements with the prism, calibrated against the standard blackbody source, gave a value of 8.1 W/μm/sr for the power in the 4.4-μm band produced by the 2.5-cm-diameter portion of the flame. The width of this band is about 0.3 μm, so this is about 2.4 watts/sr, or 30 watts. The Fourier transform spectrum can be integrated to find the proportion of the total output which was due to the 4.4 μm band; this turns out to be 24%. Therefore, the total IR output (as measured by the MCT detector) of the 2.5-cm portion was about 125-watts. The average ratio between the entire flame and the 2.5-cm-diameter portion in Table II is 10.1, so the total IR output is about 1250 watts. At a distance of 121 cm (4 ft), the power density would then be about 0.007 watt/cm^2.

Although room temperature detectors would have less sensitivity than the liquid-nitrogen-cooled detector used in these measurements, the signal was not only well above the detection level, but at 4 ft it was above the saturation

level of the amplifier, with no optics used to concentrate the IR radiation. This suggests why the standard flame is detectable at 4 ft, even with room temperature detectors.

AN ALTERNATE CALIBRATION SOURCE:

It would be convenient for some purposes to replace the standard source with one that would have similar spectral characteristics, but which could be more easily controlled and cleaner burning. Figure 6 is a Fourier transform spectrum of a common propane torch flame (propane + air). Typical of hydrocarbon flames, the spectrum is dominated by the 4.4-μm emission. The chief difference between the propane spectrum and the standard JP-4 diffusion flame is the lack of an underlying broadband emission in the propane flame. This is due to the fact that propane burns cleanly, with few particulates to provide blackbody-like radiation. A reasonable approximation to the standard flame could be produced by a large propane torch, plus a broadband radiator, perhaps a refractory material heated electrically (Fig. 7(a)). The size of the propane burner and the flow rate could be adjusted to produce a total IR output similar to that of the standard flame. Or, material could be introduced into the flame to produce thermal radation (Fig. 7(b)).

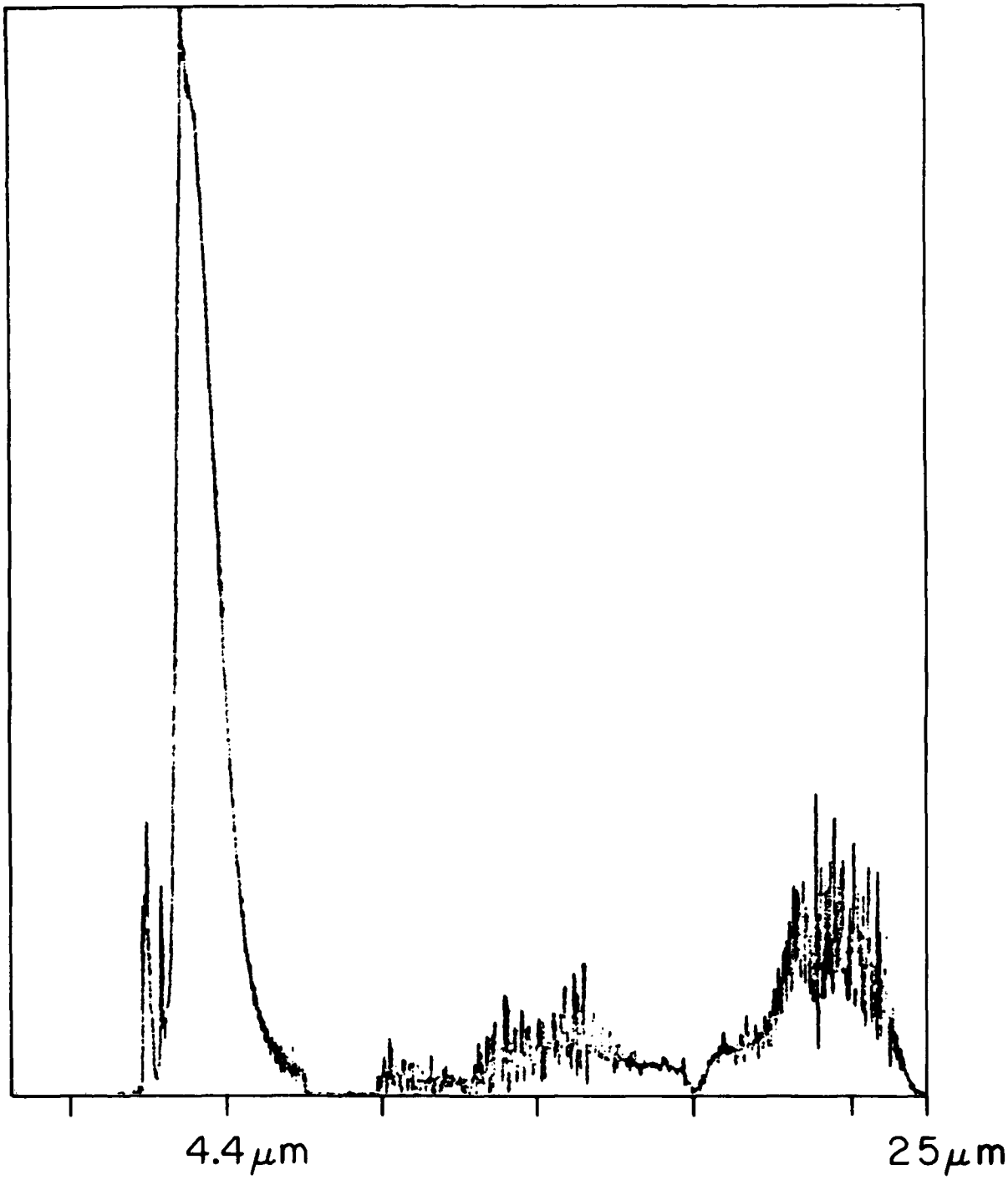
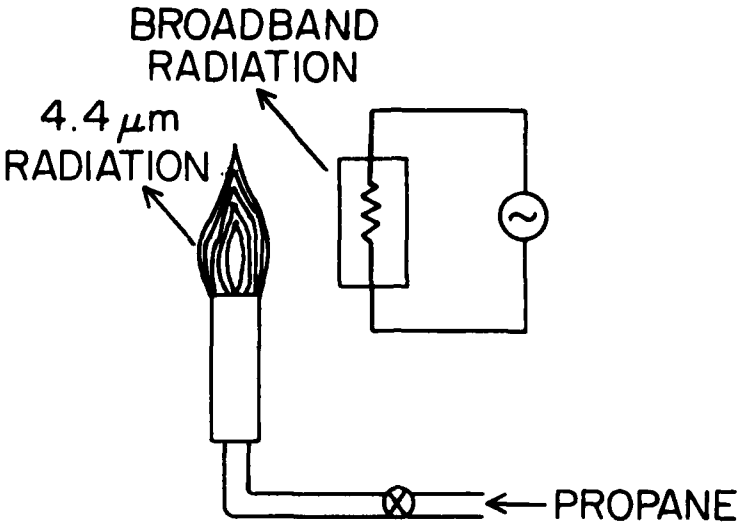
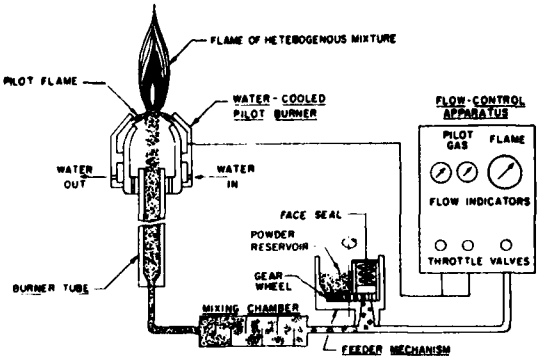


Figure 6. (Propane + Air) Flame FTS Scan
(Relative Intensities)



a. (Propane + Air) Flame Coupled with a Broadband Radiation Source



b. Metal Powder-Oxygen Flame Apparatus

Figure 7. Schematics of Possible Alternate Sources

DISCUSSION

The results of this work were consistent with those of Linford and Dillow in the spectral region examined (2.5 to 20 μm). It is difficult to quantitatively compare the 4.4-μm measurement in this work to those of Linford and Dillow, because of the different conditions. Their 4.4-μm results (1.5 to 2 W $\mu m^{-1} sr^{-1}$ at sea level) refer to the entire output of their flame, while the result given in this work (1.73 W $\mu m^{-1} sr^{-1} cm^{-2}$) is normalized to a 1-$cm^2$ portion of the flame imaged on the monochromator's entrance slit. However, to the extent that the 4.4-μm emission can be expected to be similar in both works, it appears that a 1-cm^2 area of the flame used in this work is roughly equivalent in total output to the flame used by Linford and Dillow.

An alternate calibration source would have to emulate the 4.4-μm band emission and the broadband thermal emission. The first is typical of hydrocarbon flames, the second of heated solids. Many combinations of 4.4 μm and thermal sources might be used.

APPENDIX A

CALCULATION OF THE SPECTRAL RADIANT EMITTANCE

Table I includes the measured signals of the flame and blackbody reference, and the spectral radiant emittance of the flame derived from these measurements. The spectral radiant emittance of the blackbody (power emitted per unit area of radiator per unit wavelength) is given by the Planck blackbody law

$$m_\lambda(T) = 2\,h\pi c^2/[\lambda^5(e^{hc/\lambda kT}-1)] \quad ,$$

where $m_\lambda(T)$ is the spectral radiant emittance at wavelength λ, T is the absolute temperature, h is Planck's constant, c the speed of light, and k Boltzmann's constant.

Assuming linearity of the detection system, the spectral radiant emittance of the portion of the flame in the field of view is simply $m_\lambda(T)$ of the reference blackbody multiplied by the ratio of the flame signal to the blackbody signal. This gave a flame spectral radiant emittance of 1.73 W $\mu m^{-1} sr^{-1} cm^{-2}$ at 4.4 μm. The total radiance of the portion of the flame in the field of view was then the area of the field of view multiplied by 1.73 W $\mu m^{-1} sr^{-1} cm^{-2}$, or 8.1 W $\mu m^{-1} sr^{-1}$.

APPENDIX B

MEASUREMENTS WITH NARROW-BANDPASS FILTERS

A series of measurements were made using narrow bandpass IR filters, with bandpass centers ranging between 1.8 to 2.7 μm.

Unfortunately, the narrow bandpass filters have two bandpasses, one centered at the wavelength indicated and one in the 4 to 5 μm region. The transmittance of the so called 2.3-μm filter, as measured using the Nicolet FTS, is shown in Fig. B1. (The apparent transmittance near 3600 cm^{-1} is due to ratioing against a background containing atmospheric water vapor.) As a result, these measurements represent a superposition of flame radiance from the 4.4-μm CO_2 region with the indicated filter region.

The results of the filter measurements are shown in Fig. B2. The vertical scale should not be taken as quantitatively accurate, due to the mixture of frequencies.

The measurements plotted as squares were taken at the beginning of the fuel burn, while those plotted as triangles were taken at the end of the burn. The lack of dependence of the radiance on burn time is evident in Fig. B2.

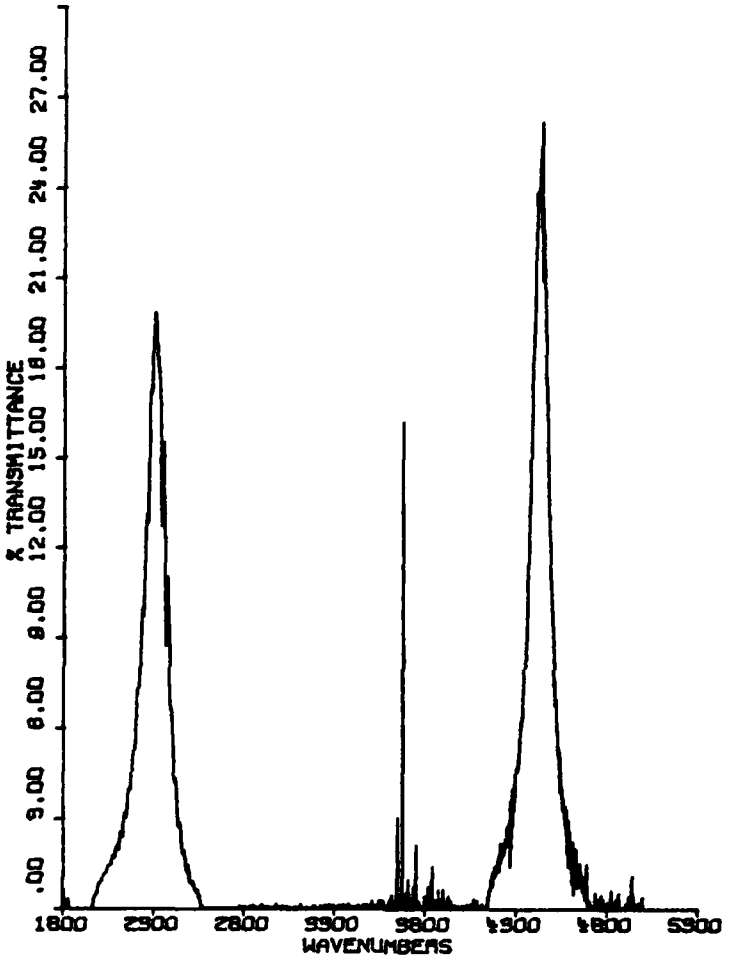


Figure B-1. Transmittance of 2.3-μm Filter

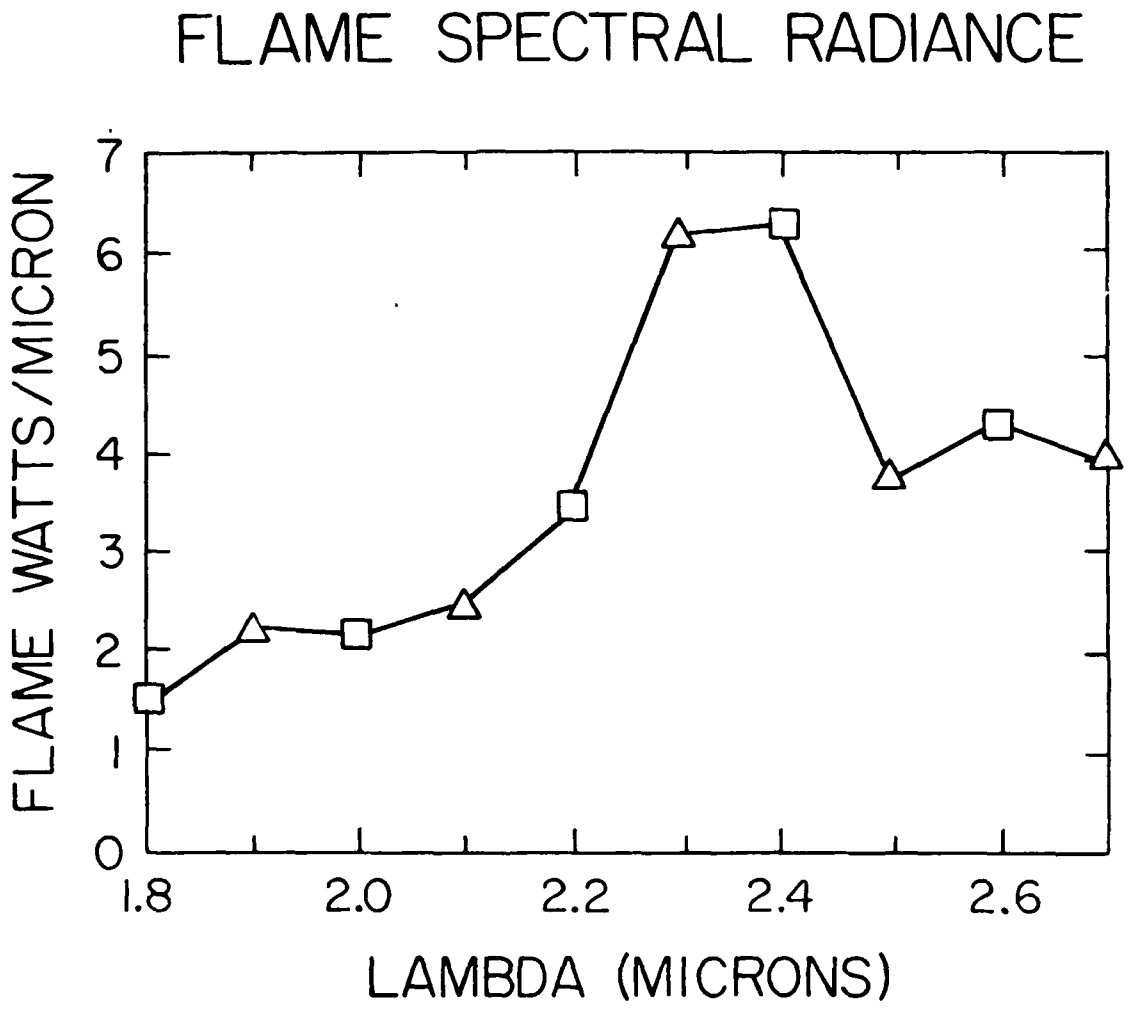


Figure B-2. Filter Measurements

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